Technical Note 1968-3

Some Observations of Weak Japanese Earthquakes at the Montana LASA

R. M. Sheppard
E. J. Kelly
H. W. Briscoe

8 January 1968

Prepared for the Advanced Research Projects Agency
under Electronic Systems Division Contract AF 19(628)-5167 by

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Lexington, Massachusetts

The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology. This research is a part of Project Vela Uniform, which is sponsored by the U.S. Advanced Research Projects Agency of the Department of Defense; it is supported by ARPA under Air Force Contract AF 19(628)-5167 (ARPA Order 512).

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

SOME OBSERVATIONS OF WEAK JAPANESE EARTHQUAKES AT THE MONTANA LASA

R. M. SHEPPARD
E. J. KELLY
H. W. BRISCOE

Group 64

TECHNICAL NOTE 1968-3

8 JANUARY 1968

LEXINGTON MASSACHUSETTS

ABSTRACT

Data on small local earthquakes were obtained from a tripartite located on the island of Honshu, Japan. Epicenters and origin times were computed from the data but local magnitudes could not be determined. LASA beams were formed at and around the computed epicenters to determine if the event could be detected on the array. From the original population of about 150 events, only 28 could be detected or were marginal. The LASA epicenters were obtained by beamsplitting and were found to be consistent with the theoretical location errors expected for beams steered to Japan. Although the total number of events visible at LASA were small, it was consistent with a beam detection threshold of 3.5 for beams steered to Japan.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

I. SUMMARY OF THE EXPERIMENT

At the time of the installation and initial operation of the Large Aperture Seismic Array (LASA) in Montana, evaluation of its performance was hampered by the lack of a reference population of small teleseismic events. In an early attempt to provide such a reference, for at least one small epicentral region, Lincoln Laboratory sent an analyst to Tokyo, Japan, during the summer of 1966. Data was collected from the seismic tripartite operated by the University of Tokyo's Earthquake Research Institute. It was hoped that this data would provide a reference population of small events with precise locations and magnitudes so that detection thresholds and location accuracy of LASA could be studied in detail, at least for one source region.

Unfortunately, the problems associated with interpretation of data from the tripartite for local events, particularly the magnitude determination, were more serious than expected. It was possible to use the data only to determine the existence, approximate location and origin time of local events. The experiment was further hindered by the fact that there were so many small local events detected in Japan that it was impractical to save LASA tapes for each one. It took several weeks to work out acceptable communications and procedures for saving the appropriate LASA data. In the final analysis there were approximately 150 events that were recorded on the tripartite for which LASA data were available for analysis. This population reduced to 28 events that were large enough to be conceivably detected by LASA, the remaining events being eliminated when it became evident that none of the smaller events would be detected.

For those events that were detected in off-line beams, formed by combining the straight sum output of each subarray, the amplitude and period of the best beam for each event was used to compute the LASA magnitude. The resulting magnitudes are not inconsistent with a LASA beam detection threshold for teleseismic P-waves of about 3.5.

The LASA locations were determined by forming a grid of beams covering the epicenter determined from local tripartite data and choosing the best beam. The location error is magnitude dependent at small magnitudes. For most events, the location indicated by the best beam was within 150 kilometers of the location determined from local data, the largest difference between the local and LASA epicenter being 400 kilometers.

II. DATA REDUCTION

During the two months of August and September of 1966, arrival times and amplitudes of P and S waves were read from recordings obtained from the three station network operated by the Earthquake Research Institute in Tokyo, Japan. The data obtained from the tripartite were similar in format to data sent to the U. S. Coast and Geodetic Survey. The objective was to reduce this data to obtain accurate epicenters and magnitudes for comparison with LASA beamforming data.

Use of the tripartite to determine magnitudes proved to be a problem. The time scale on the chart recordings was too compressed to allow a measurement of the dominant period, and since the period changes significantly between events, particularly at different ranges, it was impossible to determine a consistent magnification. The instrument response for the three stations in the tripartite is shown in Fig. 1. The magnitude problem was further complicated by the fact that the instruments saturated at about 1.5 microns so that amplitudes for large events could not be measured.

The locations of the three stations are as follows:

Tsukuba	Lat.: 36.211^{o} N	Long.: 140.110^{o} E
Dodaira	Lat.: 36.003^{o} N	Long.: 139.193^{o} E
Kiyosumi	Lat.: 35.200^{o} N	Long.: 140.141^{o} E

Data for each event consisted of at least two P-arrival times and at least one S-P interval. Many events were recorded by all three tripartite stations. For some events, one station was noisier than the others, and frequently provided only a P-arrival time of relatively low accuracy. Instead of using a least-squares procedure for determining epicenters, based on a variable number of measurements, an algorithm was used for finding a unique pair of epicenters from two P-arrivals and the S-P interval from one of these stations. The difference in P-arrivals puts the epicenter (assumed to be at the surface) on a hyperbola, and the S-P interval puts it on a circle, which intersects the hyperbola in two points. The ambiguity is resolved by the third P-arrival, when available. Details are given in the Appendix.

All possible combinations of two P-arrivals and one S-P interval were worked up for each event, and all the resulting epicenters for each event were plotted on a map. For events having redundant data, the resulting epicenters were "averaged" by eye, leaving one or at most two epicenters per event. This manual averaging (which is analogous to a least-squares procedure) permitted the exercise of judgment in rejecting solutions thought to be out of line because of poor data.

For each event, the expected LASA arrival time was computed for one or both epicenters, and the LASA data searched for the event. Although LASA was not recording on a 24-hour basis and it was not possible to save recordings of each event reported, digital tapes were saved which included the expected arrival times of about 150 of the events located from tripartite data.

After the epicenters were computed for the population of events, a grid of beams at 50 km spacings was formed around the epicenters. The beams were formed by phasing and adding the subarray straight sums using the standard Jeffreys-Bullen travel time tables and station corrections prepared by Earth Sciences, a Teledyne Company.[1] Beamforming started with the largest events and worked down until it was evident that no smaller events would be detected. In this manner, the original population was reduced to 28 events that were clearly seen or were considered to be marginal. Additional information on these events is given in Table I.

TABLE 1

EVENT LIST

1966 Date	Origin GMT	Latitude	Longitude	Expected LAO Arrival	Magnitude	Detected	PDE Card
8/19	06 22 19	32.1 N	139.3 E	06 34 37	4.8	Yes	
8/19	06 26 38	32.0 N	139.0 E	06 38 57	4.5	Yes	
8/20	08 31 45	19.1 N	144.3 E	08 44 36		Questionable	
8/20	09 32 32	43.1 N	140.6 E	09 43 44	5.8	Yes	61
9/02	10 19 55	37.0 N	139.5 E	10 31 51	3.6	Yes	
9/03	08 11 39	43.2 N	146.5 E	08 22 44	4.6	Yes	64
9/10	02 27 48	46.6 N	144.1 E	02 38 16	5.2	Yes	65
9/11	06 51 45	41.4 N	143.0 E	07 03 13	4.0	Yes	
9/11	17 33 30	38.2 N	137.3 E	17 45 28	3.5	Questionable	
9/15	03 27 07	36.6 N	138.2 E	03 39 09		Questionable	
9/17	06 32 21	27.0 N	142.5 E	06 44 49	3.6	Yes	
9/18	05 22 31	42.3 N	142.8 E	05 33 51	5.1	Yes	67
9/18	08 14 08	35.1 N	142.7 E	08 26 02	3.6	Questionable	
9/18	10 28 29	35.9 N	139.8 E	10 40 29	3.4	Questionable	
9/21	04 02 14	36.9 N	133.9 E	04 14 27	3.6	Yes	
9/21	06 03 18	39.5 N	144.3 E	06 14 48	3.6	Yes	

9/22	04 15 31	37.3 N	138.6 E	04 27 26	4.9	Yes	68
8/20	09 32 37	36.6 N	138.2 E	09 44 39		No	
9/15	06 19 01	37.1 N	139.5 E	06 30 56		No	
9/16	08 00 01	37.1 N	138.7 E	08 11 59		No	
9/16	09 49 39	35.6 N	139.8 E	10 01 41		No	
9/16	10 16 04	31.9 N	139.5 E	10 28 22		No	
9/16	11 36 02	41.2 N	143.4 E	11 47 29		No	
9/17	11 23 37	39.1 N	136.8 E	11 35 32		No	
9/18	06 42 01	36.5 N	140.3 E	06 53 57		No	
9/18	08 40 53	39.3 N	141.1 E	08 52 35		No	
9/21	10 12 01	35.9 N	142.7 E	10 23 53		No	
9/22	02 58 41	32.1 N	138.8 E	03 11 00		No	

III. DETECTION THRESHOLD

In an earlier report,[2] it had been estimated that the Montana LASA, using subarray outputs could detect 50% of the teleseismic P-wave arrivals of magnitude 4.1 or greater and that therefore the corresponding magnitude threshold when beams were used should be 3.5. One of the objectives of this experiment with Japan data was to check this assertion. Figure 2 shows a plot of the number of events detected versus magnitude. The number of events detectable on LASA beams is much too small to allow an accurate estimate of the detection threshold, but the magnitude of these events seen and the noise level on the beams are not inconsistent with a detection threshold of about 3.5 for beams steered to Japan.

IV. EPICENTERS DETERMINED BY BEAMSPLITTING

The epicenters obtained from the Japan tripartite data were thought to be within a LASA beamwidth (8°) of the true epicenters. It was desired to test the location ability of the LASA by the technique of "beamsplitting", that is, careful determination of the direction of aim of the LASA beam that produces the greatest signal output. The population of 28 events was analyzed in this manner. The results produced 12 events which could be clearly seen and identified, five events which were marginal and considered questionable, the remaining 11 events being definitely not visible even on filtered beams.

The locations of the computed epicenters were compared with the locations of the best beam resulting from the grid of beams. The difference in the two epicenters was plotted against the LASA magnitude. In most cases the best beam was within 1.5 degrees (166 km) of the computed epicenters. The results for the 12 clearly seen events are shown in Fig. 3. The curve is a theoretical formula for beamsplitting accuracy based on idealized models of the signal, noise and the measured process. The theoretical model of the signal assumes perfect knowledge of time delay station corrections.

By expanding the grid of beams from the original 16 to 400 and measuring the output power of the signal in each beam and then contouring the signal outputs, one obtains a true picture of the actual beam pattern.[3] Figures 4 and 5 show the results of performing this operation on two of the 12 detected events listed in Table 1.

V. CONCLUSION

Although the attempt to measure the Montana LASA teleseismic detection threshold did not prove definitive, the results are encouraging. The experiment should be reported for other situations where both the LASA and a local network monitor low-magnitude seismic activity in a region distant from Montana, for example the Kurile Islands ocean bottom experiment of late 1966.

The present experiment has provided a meaningful determination of epicenter location error using beamsplitting of a single LASA for a source region in which the station corrections are well known.

ACKNOWLEDGEMENT

The data from the tripartite of stations at Tsukuba, Kiyosumi, and Dodaira was made available to us through the generous assistance and cooperation of Prof. Setumi Miyamura and his associates, in particular Mr. Masaru Tsujiura, at the Earthquake Research Institute of the University of Tokyo.

The records from the tripartite were read and the preliminary analysis performed by Mr. John Fairborn, a student at the M. I. T. Geophysics Department.

REFERENCES

1. "Travel-Time Anomalies at LASA," Earth Sciences, A Teledyne Company, Report No. LL-6, 7 July 1967.

2. P. E. Green, Jr. and R. V. Wood, Jr., "Large Aperture Seismic Array Capabilities," Technical Report 421, Lincoln Laboratory, M. I. T., 12 July 1966 DDC 639197.

3. Seismic Discrimination, Semiannual Technical Summary Report, Lincoln Laboratory, M. I. T., 30 June 1967, see Section III-D DDC 657327.

4. Staff of the Earthquake Research Institute, Tokyo University, "Explosion Seismological Research in Japan," in The Earth Beneath the Continents, Geophysical Monograph No. 10 of the American Geophysical Union, by Steinhart and Smith.

APPENDIX

The population of events used in this experiment ranged in location from sources within the tripartite to epicenters several hundred kilometers away. We have no real idea what the distribution of events was in depth of hypocenter, and all events were assumed to have surface foci. It is therefore not to be expected that a simple algorithm will provide high accuracy in location and it is also not easy to infer from known properties of the region what method to use for epicenter location.

The procedure we used requires two basic formulas: one to give difference in distance to two stations from a measured difference in P-arrival times and a second to give distance itself from a single station using a measured S-P interval. If the travel-time for P is a linear function of distance, such as

$$T_P = T_0 + (\Delta/V_P) \ ,$$

then the first required formula is

$$\Delta_2 - \Delta_1 = V_P(T_2 - T_1)$$

The measured P-arrival times are T_1 and T_2 and V_P is assumed P-speed. Note that the constant, T_0, is not used. We used the value 7.5 km/sec for V_P, which is typical of P_n speeds in Japan.[4]

In order to get distance from the S-P interval, T_{SP}, we used the relation

$$\Delta = A\,T_{SP} + B\,T_{SP}^2 \quad ,$$

where

$$A = 7.86 \text{ km/sec}$$

and

$$B = 0.04 \text{ km/sec}^2$$

The small quadratic term was used to increase the (Δ/T_{SP})-ratio from a value near 8 km/sec, thought to be typical of near events, to a value near 10 km/sec for a distance of 500 km. The value 10 km/sec is consistent with Jeffreys-Bullen travel times for distances in the 500 – 1000 km range. In other words, we tried to interpolate between a value used in Japan for locating local events and the standard tables for events at relatively great distance.

A limited amount of experimenting with other constants in these formulas showed that our events were just as consistently located (i.e., epicenters from redundant data on one event were in good agreement) by a linear relationship between distance and S-P interval. If one assumes that both the P and S travel time curves are linear, and that one has S-P measurements for two stations, $(T_{SP})_1$ and $(T_{SP})_2$, as well as their P-arrival times, P_1 and P_2, then it follows that

$$\frac{(T_{SP})_2 - (T_{SP})_1}{P_2 - P_1} = \alpha - 1 \quad ,$$

where $\alpha = V_P/V_S$ is the ratio of P to S speeds. We measured this ratio for all events in the population, with the average result $\alpha = 1.81$. This ratio requires an S speed of

4.14 km/sec, to be consistent with our assumption of the value 7.5 km/sec for P. These speeds in turn imply the relation

$$\Delta = 9.2\, T_{SP}$$

for distance in terms of S-P interval. Our quadrant formula predicts the ratio $(\Delta/T_{SP}) = 9.2$ at a distance of 300 km. Since the average distance of the events from the center of the tripartite is several hundred kilometers, our formulas for epicenter accuracy are in reasonable agreement with the data itself.

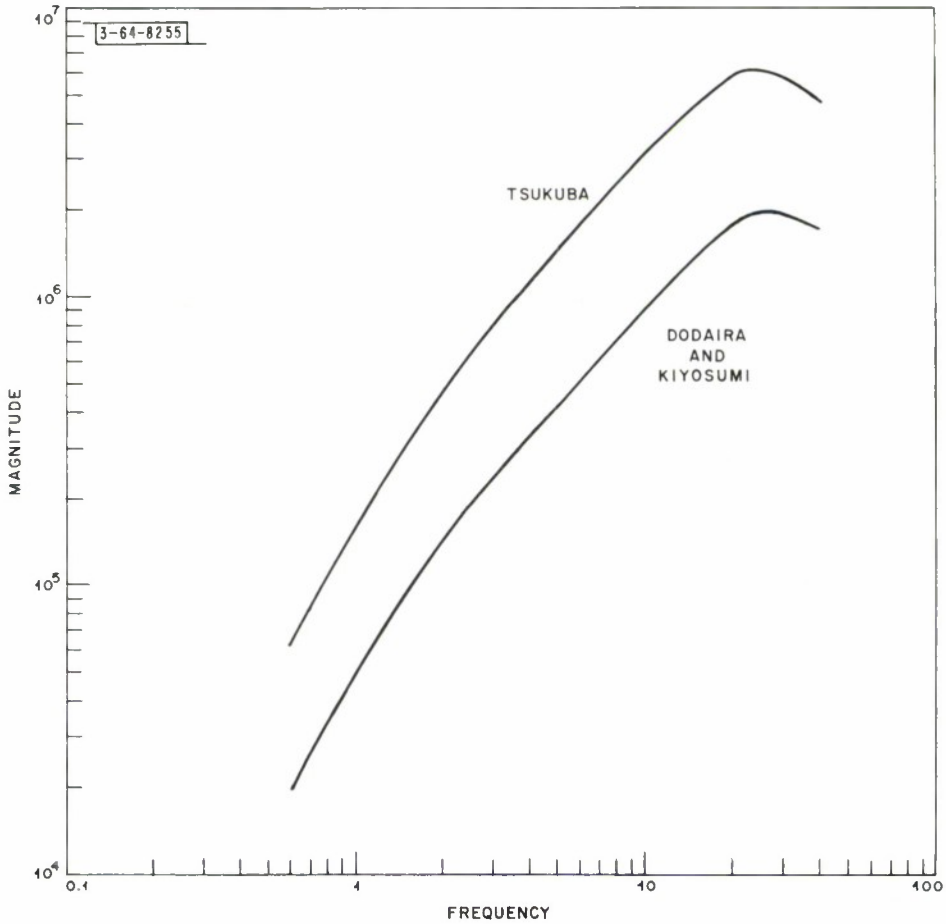

Fig. 1. Instrument magnification.

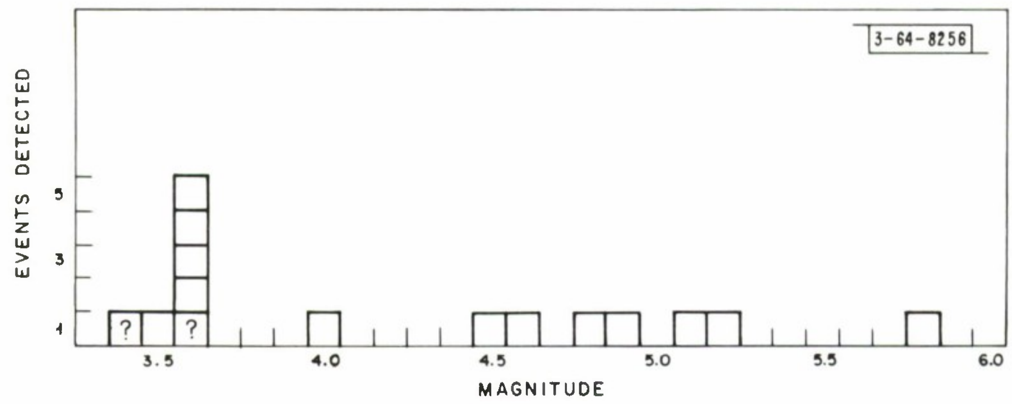

Fig. 2. Detected events.

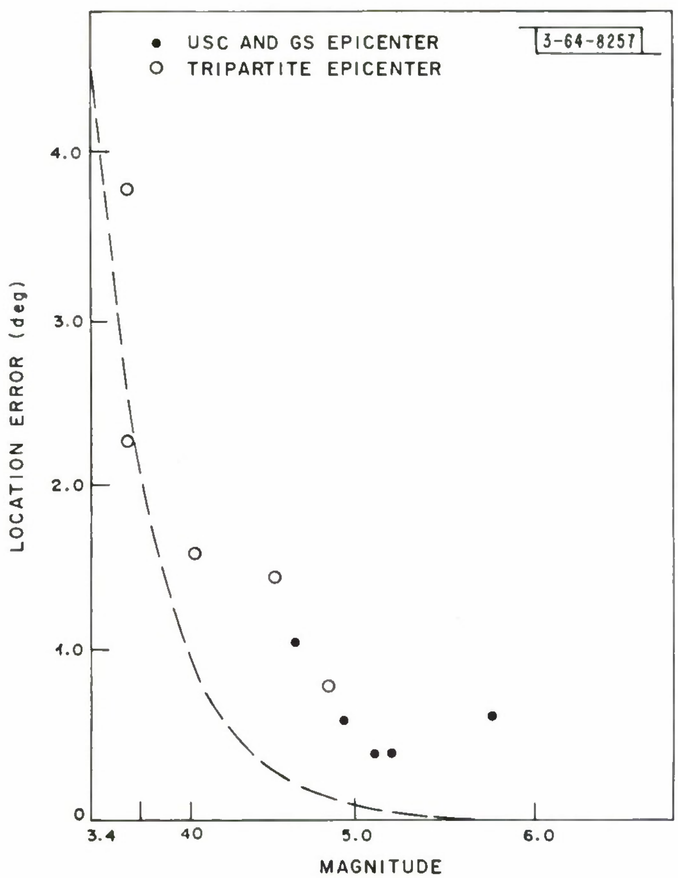

Fig. 3. Epicenter error.

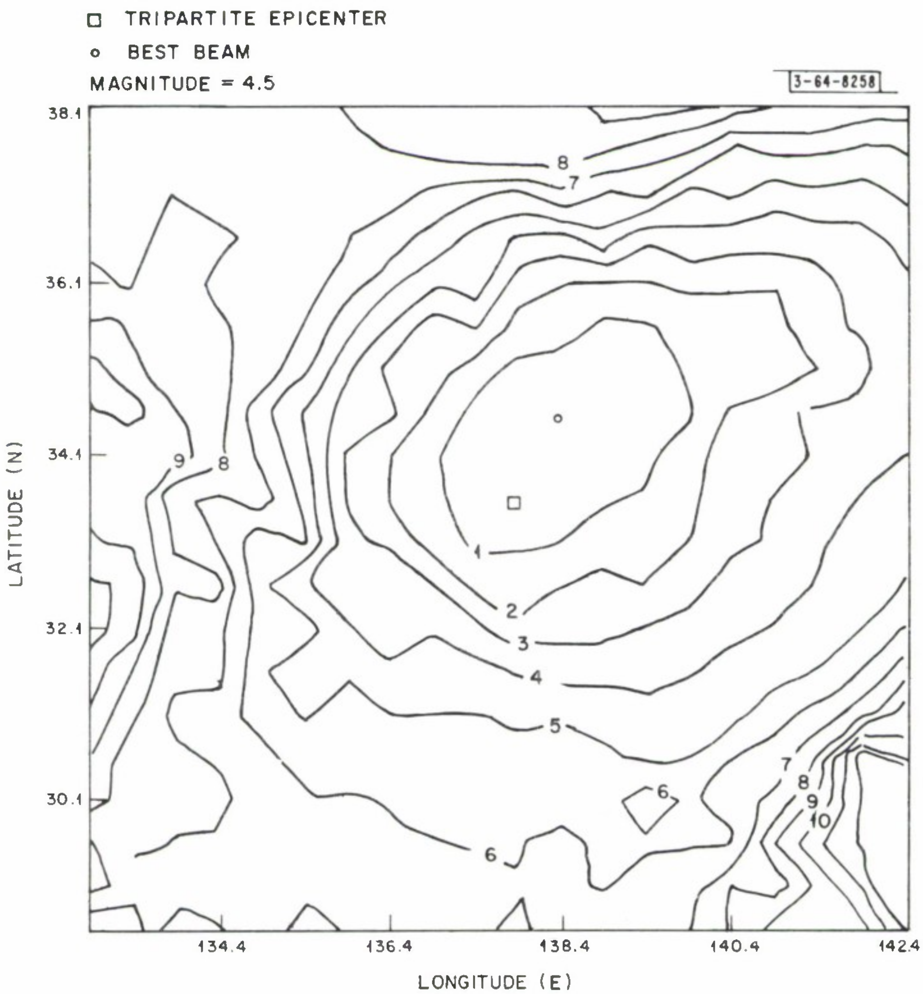

Fig. 4. Actual beam pattern.

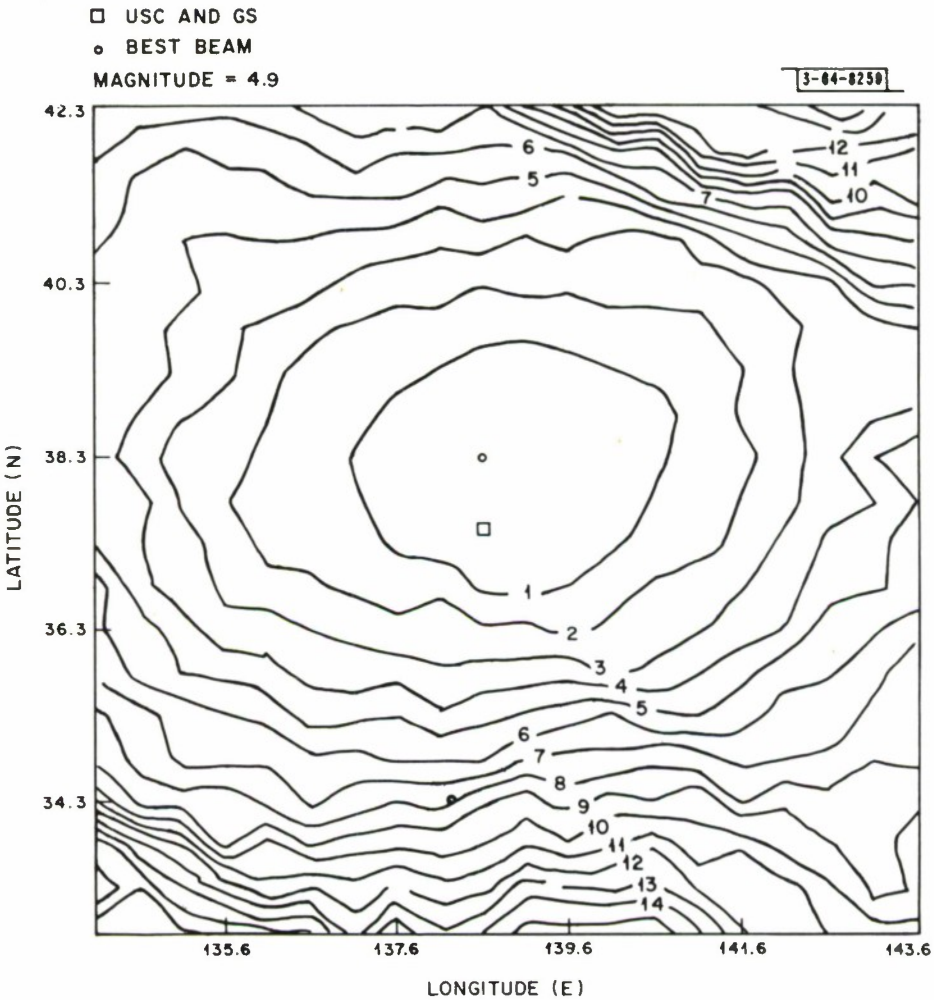

Fig. 5. Actual beam pattern.

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Lincoln Laboratory, M. I. T.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP None

3. REPORT TITLE

Some Observations of Weak Japanese Earthquakes at the Montana LASA

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Technical Note

5. AUTHOR(S) *(Last name, first name, initial)*

Sheppard, Robert M. Kelly, Edward J. Briscoe, Howard W.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
8 January 1968	22	4

8a. CONTRACT OR GRANT NO. AF 19(628)-5167	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Note 1968-3
b. PROJECT NO. ARPA Order 512	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* ESD-TR-67-598
d.	

10. AVAILABILITY/LIMITATION NOTICES

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	Advanced Research Projects Agency, Department of Defense

13. ABSTRACT

Data on small local earthquakes were obtained from a tripartite located on the island of Honshu, Japan. Epicenters and origin times were computed from the data but local magnitudes could not be determined. LASA beams were formed at and around the computed epicenters to determine if the event could be detected on the array. From the original population of about 150 events, only 28 could be detected or were marginal. The LASA epicenters were obtained by beamsplitting and were found to be consistent with the theoretical location errors expected for beams steered to Japan Although the total number of events visible at LASA were small, it was consistent with a beam detection threshold of 3.5 for beams steered to Japan.

14. KEY WORDS

earthquakes	teleseismic	seismic array
LASA	beamsplitting	